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Review Article

Nanoparticles in drilling fluid: A review of the state-of-the-art

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ABSTRACT

Nanoparticles (NPs) as a nanotechnologies unit have a huge potential for improving drilling fluids. However, the role of NPs in this field is still in its infancy and consequently has attracted much more attention in the last years. This review is going to investigate the drilling fluids modified by nanoparticles. Moreover, effects of various nanoparticles include polymeric, ceramic, metal and carbon-based NPs on drilling fluid and technical and economic benefits of them will be inspected. Although various reviews of nano-based drilling fluids have been reported, few papers have provided a comprehensive review and development of nanoparticles application in this issue. This review summarizes the recent research advances in the synthesis and applications of NPs in drilling fluids system. The roles of NPs in rheology and fluid loss control, mud cake thickness, filtration properties, and thermal properties are discussed. Accordingly, various literature reviews demonstrated that use of nano materials in drilling fluid has two main goals: improvement of thermal and physical-mechanical of drilling fluids. The studies in this issue will facilitate the design of advanced functional nano-composites for drilling fluids.

1. Introduction

Natural gas and oil (global primary energy resources) production have demonstrated considerable gain caused by the rising world energy demands and energy consumption. Therefore, new and evolving technologies in oil production such as directional drilling and horizontal hydraulic fracturing are rapidly reshaping [1–7]. Drilling fluids play a significant role in drilling oil and gas reservoirs process. Due to technical, economical, and environmental issues, they are challenging subject matter [8].

The drilling fluid has some significant functions such: 1) remove cuttings rocks from the bottom of wells and transport to the surface, 2) lubrication and cooling bits and drill strings 3) creation a thin filter cake with low permeability for sealing pores of rock formation in wells, 4) preventing enter formation fluid into wells by providing hydrostatic pressure, and 5) reducing the coefficient of friction between the hole and the drilling string [9,10].

According to recent developments in nanomaterials technologies, in the last decade, some researchers most widely have used and evaluated nanoparticles in the oil and gas industry [11–22]. Consequently, one main usage of nanomaterials in the oil and gas industry is in the section of developing novel kinds of drilling fluids [23]. The investigations result and analysis show that NPs can be used as suitable additives to improve drilling fluid properties [16,19,24]. Therefore, the advantages of mechanical, hydrodynamic, thermal, electrical chemical properties and

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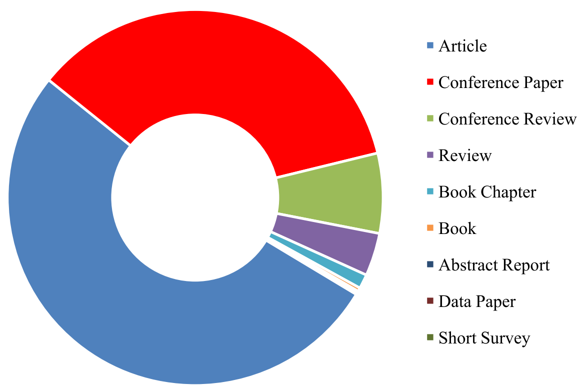
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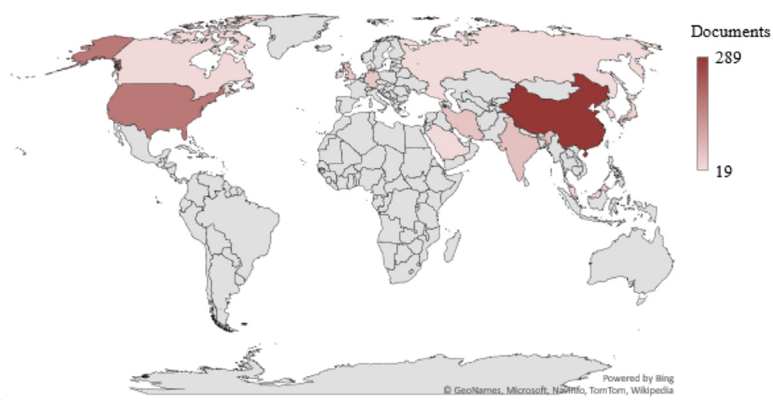
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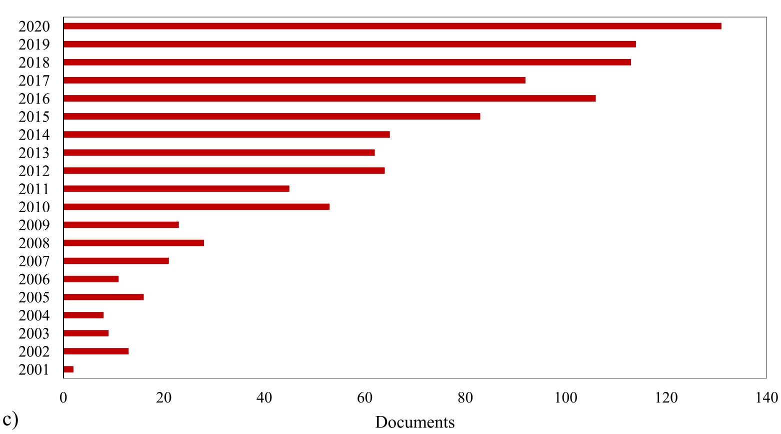
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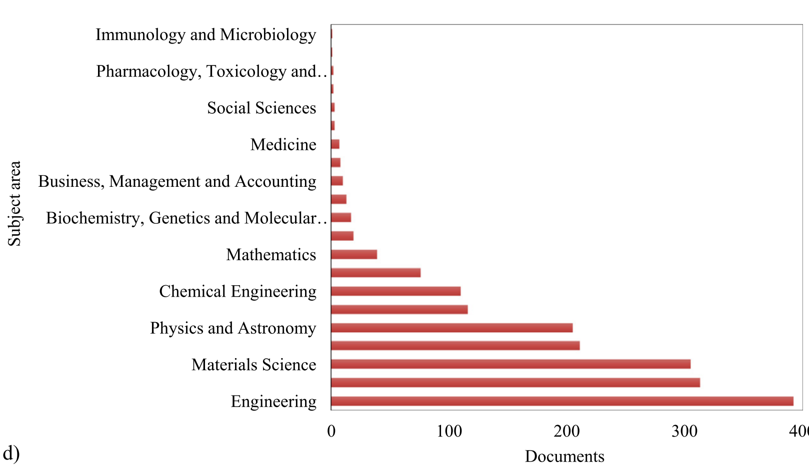
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interaction potential of NPs compared to their base materials, causes that nanoparticles are considered as an excellent choice for applications in drilling fluids [12]. Nanomaterials due to remarkable thin and fine formation have huge abilities to decrease the frictional resistance between drilling pipes and side hole and improve torque and dragging. Moreover, NPs have extensive capabilities drilling in high pressure and high temperature (HPHT). The heat transfer performance of conventional drilling fluids can be altered to possibly better control cooling of drilling instruments. Therefore, the chance of destruction of drilling tools increases at HPHT condition. The wider surface area of NPs cause increase thermal conductivity of drilling fluid and thus improve heat transfer in drilling tools [25,26].

Over the years, different types of NPs were evaluated to produce nano drilling mud in some cases addressed as nano-reinforced drilling fluid. Rheological investigations showed NPs have efficient potential to development new drilling fluid [27]. Moreover, borehole stability is another problem that it has improved by using NPs as additives into drilling fluid [28]. Furthermore, NPs with reducing the content of chemical and solid can be decreasing the overall cost of drilling fluids [29–32]. In other words, a unique feature in NPs is their high ratio surface to volume, so NPs can be plug throat pores in bore hole of wells with fewer amounts of drilling fluid materials [33]. Besides, the size of particles should be shorter than pore throat (about one third) till they can plug pores in bore hole [34] and NPs are excellent materials for doing this function. The thermal conductivity ability is another advanced feature of NPs [35]. Some NPs can improve heat transfer efficiency of drilling fluid more than 20% compared to conventional mud [36–38]. During the different steps to produce and reproduce the drilling process, NPs could be decreased environmental hazard, reducing ecological risks concerns of drilling fluid [39]. Some noxious chemical compositions and heavy metals (Cu, Cr, Hg, Cd, As, and Pb) are a major environmental challenge and recent studies have shown environmentally friendly NPs have potential to controlling harmful effects of them [40,41].

In order to review the NPs used in drilling fluids, more than 503 research papers on the issues or related to these subjects (2002–2020) were selected. Then, 180 up to date articles, with priority the latest research in recent years (2016–2020), were chosen for detailed evaluation. All of the statistics are extracted from the Web of Science, Scopus, Google Scholar, SCImago-Journal databases. According to these data, between 1997 and 2020, 1062 documents published. Fig. 1 reports the numbers of scientific publications, document types in nano drilling fluids. Types of documents show in Fig. 1a such based on article, review, book, document, and conference. The number of documents based on countries, by year, and based on subject area indicated in Fig. 1 b–d, respectively.

This article summarizes and analyzes the published laboratory results. The objective of this study is to give a thorough review of available NPs used in drilling fluids from the perspective of interdisciplinary and to try to provide directions for future investigations of NPs-based drilling fluid systems.

2. Nanoparticles in drilling fluids

Application of nanoparticle in drilling fluid technology is one of recent progress in the oil and drilling industries [42–45]. NPs with unique properties such as high thermal conductivity and wide surface area can be solved drilling fluid challenges. Reduction in formation damages, and overall drilling fluid cost, control fluid loss and mud cake, removal hazard materials, improvement heat transfer, lubrication, and rheological properties such as viscosity, are main advantages of using NPs in drilling fluids [46–48]. Some nanoparticles used in drilling fluid have been shown in Table 1.

2.1. *Polymeric nanoparticles*

The most common compositions for producing nanocomposites are polymer materials. Depending upon the NPs constructions, used synthetic or natural type's polymers. Polymer NPs apply in various fields of science and industry from medicine and pharmaceutical, conducting materials, aerospace, sensors, electronics, Energy, and oil and gas [79–96].

2.1.1. *Synthetic polymer nanoparticle*

Sadeghalvaad and Sabbaghi had successfully synthesized polymer-nanocomposite (TiO_2/PAM) for using in WB drilling fluids system. Their results show that the nanocomposite improved volume of fluid loss, thickness of mud cake, and rheological properties [63].

Huang et al. (2018) investigated effects of introduced a nanocomposite of SiO_2/acrylic resin with a core shell construction on the rheological characteristics and thermal properties of WBD. They illustrated drilling fluids with acrylic/SiO_2 NPs increase efficiency of plugging and decrease invasion of fluid [97]. Xu [98] in new work used silica nanopoly as wetting reverse agents to changing wettability properties in shale formations. The results demonstrated that the solutions could carry nano wetting reverse agents.

In 2016, ZnO- Acrylamide composite had synthesized and successfully characterized by Aftab and co-workers. Synthesized composites modified chemical and thermal properties of drilling fluids. Synthesized composites in drilling fluids illustrated that filtrate loss, lubricity, yield point, and gel strength were modified. Therefore, composite of ZnO with polymer can be a suitable drilling fluids additive to modify shale swelling and rheological behavior at high temperature condition [99].

The combination of polyethylene glycol and nano-silica was investigated in a recent research work by Xu et al. (2018) to produce WBD modified by silica NPs. The results have been indicated that this formulation could be a good shale stabilizer in WBD. In addition, it was used as plugging agent to plug shale pores and cracks [100]. In other research Mohamadian

Fig. 1 – Statistical data for nano drilling fluids; a) types of documents, b) the number of documents based on countries, c) the number of documents by year, and d) the number of documents based on subject area.

Table 1 – Reported type of nanoparticles used in drilling fluids and their behavior.

Author (s)	Nanoparticles type	NP size (nm)	Optimization	Optimal concentration of NPs	Drilling fluid type	LTLP	HTHP	Salinity	Reference
Jung et al.	Fe_2O_3	3 and 30	Rheology and fluid loss control	0.5% wt.	WBM-5% wt. bentonite		–	–	[49]
Barry et al.		3 and 30	Controlled viscosity at HPHT	0.5% wt.	WB 5% wt. bentonite	o 14%	o 37% and 47%	–	[50]
Contreras et al.		–	fluid loss control	0.5 and 2.0 wt%	OBM- Oil/Water Ratio (90/10)	o	o	10%	[51]
Barry et al.	Fe_2O_3 - Clay Hybrid	3 and 30	Increased the rheological properties	0.5% wt.	WBM-5% wt. bentonite	o	o	–	[50]
Wang et al.	Fe_3O_4	10–20	Increased the rheological and filtration properties Improved thermal properties	0.05–0.5 wt%	WBM-4% wt. bentonite		o	–	[52]
Alimohammadi et al.		16	Cd removal from drilling fluid (environmental-friendly)		WBM-bentonite		–	–	[53]
Mahmoud et al.	SiO_2	50	Rheology stability	0.5% wt.	WBM-7% wt. bentonite	o	o		[54]
Li et al.			Increased the rheological and filtration properties		WBM-bentonite				[55]
Javeri et al.			Reduced the mud cake thickness						[56]
Ismail et al.		12	The lubricity of water-based drilling fluids		WBM-bentonite		o		[57]
Kang et al.		10–20	Rheology and fluid loss control	5–10% wt.	WBM and OBM-3% wt. bentonite	–	–		[58]
Cheraghian et al.		20	Increased the rheological and filtration properties	0.5% wt.	WBM-5% wt. bentonite	o	–		[59]
Agarwal et al.	Clay		Controlled viscosity at HPHT		WBM-bentonite				[60]
Abdo and Haneef		10–20	Controlled viscosity at HPHT				o		[61]
Cheraghian			Increased the rheological and filtration properties		WBM-bentonite				[62]
Sadeghalvaad and Sabbaghi	TiO_2	10–15	Increased the rheological and filtration properties	0.5–10% wt.	WBM-bentonite	o	–		[63]
Sabbaghi et al.		20	Improved thermal properties	0.1–0.3% volume fraction	WBM-bentonite	–	–		[64]

Anawe et al.,	Y_2O_3	20–30	Increased the rheological and thermal properties	0.5–3% wt.	WBM-bentonite	o	o			[65]
William et al.	CuO and ZnO	<50	Improved thermal properties at HP/HT conditions	0.1–0.5% wt.	0.4 wt% XG in water	o	o			[16]
Ponmani et al.		–	Reduced the mud cake thickness	0.1–0.5% wt.	WBM-bentonite	o				[19]
Gudarzifar et al.	Graphene	2.71	Rheology and fluid loss control	0.5% wt.	OBM	o	o			[66]
Kosynkin et al.		–	Rheology and fluid loss control	0.2% wt.	WBM-bentonite	o				[29]
Aramendiz		<3	Rheology and fluid loss control	0.1–0.75 % wt.	WBM-bentonite	o	o			[67]
Taha and Lee		–	Improve lubricity	–	WBM- bentonite	o	o			[68]
Ismail et al.	Multi walled carbon nanotube	30	Controlled viscosity at HPHT	0.001–0.1 ppb	WBM bentonite	o	o			[69]
Samsuri and Hamzah		8–40	Increased viscosity	0.001–0.01 % wt.	WBM- 14 g bentonite	o				[70]
Aftab et al.		100	Rheology and fluid loss control	0.1 ppb	WBM- 200 ppb Barite		o		o	[71]
Ho et al.	Carbon	<200	Improved thermal conductivity	0–1% wt.	WBM	o				[72]
Sayyadnejad et al.	ZnO	14–25	Removal of hydrogen sulfide	–	WBM- 1.5 g sodium sulfide nonahydrate					[73]
Amarfio and Abdulkadir	Al_2O_3	40	Improved thermal properties	0–1.5 gr.	WBM- 22.5 g bentonite	o				[74]
Ghasemi		20	Increased the rheological and thermal properties	0.05% wt.	OBM- Oil/Water Ratio (90/10)	o	o			[75]
Li et al.	Silber	5	Improved thermal properties	–	OBM					[76]
Al-Yasiri and Wen	Graphite-alumina	80–400	Reduced fluid loss	0–0.8% wt.	WBM- 20 g sodium bentonite	o	o			[77]
Saboori et al.	CuO	4	Increased the rheological and thermal properties	Acrylamide monomer/ CuO:10/1	WBM- 10 g bentonite	o	o			[78]

Note: *o means improvement; @LTLP Low-Temperature-Low-Pressure; @HTHP High-Temperature-High-Pressure.

et al. (2019) identified clay nanoparticles with poly (styrene-co-methyl methacrylate) reduced fluid loss about 22% and improve thermal stability. Fig. 2 displayed effect of polymer/NPs at different NaCl concentrations on the filter cake [101].

2.2. Ceramic nanoparticles

Ceramic NP is inorganic solid produced of phosphates, carbonates, carbides, and oxides. This NP has high temperature resistance and chemical inertness. It has used in imaging, drug delivery, photo degradation, and photo catalysis. Control some of ceramic NPs characteristics, such porosity, surface to volume ratio, surface area, size; they perform as medical and mechanical agents [94,102–104]. There are various studies in this field. The possibility of incorporating magnesium, aluminum and silicate NPs in WB drilling fluid was addressed by Wang et al., (2018). The mixture prepared with the WB showed improved rheological, filtration properties, and thermal stability. Moreover, the application of the magnesium aluminum silicate NPs in WB drilling could substantially decrease the use of conventional drilling fluid, which would be highly beneficial for environmentally friendly [39,105].

2.2.1. Silica nanoparticles

In recent research, Wang et al. (2019) considered the mechanical performance of drilling fluids designed with silica NPs for used into natural gas hydrate. According to their observation, the amount of hydrate formation with used hydrophilic silica NPs in drilling fluids is 10% less than ultrapure water [106]. McDonald [107] investigated drilling fluids with novel silicate potassium, which have improved shale stability and control drilling costs and time. The morphology of NPs used in shale and filter cake are shown in Fig. 3.

Hoelscher et al. [108] designed new water-based drilling fluid with silica NPs to reduction the FL in shale samples. They concluded that the NDF improves rheological properties shale formations. In a similar investigation, addition of specially designed inexpensive silica NPs studied on shale formations [109]. Six different NPs types used as WBM additives in low-solids and bentonite mud. Results showed 10 wt% concentration of nanoparticles with 7–15 nm size reduced considerably permeability of shale and interaction between the WBM and shale formations. An et al. (2016) and Ma et al. (2019) investigated effect of silica NPs as a NF loss agent in the drilling fluid. They revealed that the modified silica NPs assisted in shutting off the loss of water and plugging the shale's nanopores [110,111].

2.2.2. Zinc oxide nanoparticles

Nanocomposites based on zinc NPs were used in hydrogen sulfide adsorption in oil and gas industries [19,112]. Sayyadnejad et al. [73] removed hydrogen sulfide gas (HSG) from WMB with using nanoparticles and bulk zinc oxide. The experimental results showed that ZnO NPs with 44–56 m^2/g surface area and 14–25 nm size has better performance in removing HSG from drilling fluids. The combination of Zinc acetate dehydrate and Titanium (IV) orthotitanate was investigated in a recent research work by Perween et al. (2018) to produce water-based drilling fluids modified by $ZnTiO_3$ NPs. The results have been indicated that this formulation ($ZnTiO_3$ NPs) could properly decrease the filtrate loss volume, and also, improve rheological properties and thermal stability of drilling fluid compared with that of base fluid [113].

2.2.3. Titanium dioxide nanoparticles

A research on the use of a different NPs group was recently proposed by Bég et al., (2018). In this study, the use of titanium and silica NPs together with WBM were investigated for producing NPs drilling fluid mixtures. Lubricity and rheology were evaluated based on conventional standardize tests. Their experimental results indicated 0.60 weight percent of concentration TiO_2 NPs improve stability of formulations, lubricity and mechanical properties of drilling fluid [114]. In 2018, Ghasemi et al. worked on the thermal and rheological properties of drilling mud with TiO_2 NPs. The results showed that the yielding point, plastic viscosity, capillary suction time, and FL reduce and gel strength increase with TiO_2 NPs additives [75].

2.2.4. Cupric oxide nanoparticles

A research has been conducted to consider CuO NPs effect on the thermal properties of WBMs. In this work, Again Ponmani et al. [19] used of ZnO and CuO NPs in special drilling fluid (with polyvinylpyrrolidone, polyethylene glycol, and xanthan gum). The efficiency of nano drilling fluid is improved in comparison with micro drilling fluid. They showed that ZnO NPs improved thermal properties that have a suitable effect on cooling efficiency at surface and down hole conditions and also controlling lost fluids compared with micro drilling fluids. NPs can seal and bridge (Fig. 4) the micro cracks and pore throats of shale samples and improve stability of shale.

2.2.5. Clay nanoparticles

Clays mined pure are applied among many uses in drilling fluids [116–118]. Barry et al. investigated filtration and rheological properties drilling fluids under different conditions (high and low pressure-temperature) with clay hybrids NPs. The results have been indicated that clay hybrids (Al_2O_3–SiO_2 and iron oxide clay hybrid) NPs in drilling fluids with modification and interaction of surface charge could be reduced FL volume [119]. Khan et al. [120] simulated a new drilling fluid with clay NPs to heat concavity improvement. They concluded that the clay NPs drilling fluid improves thermal stability.

2.3. Metal nanoparticles

Metal NPs can be prepared by photochemical, electrochemical, chemical procedures. In chemical process, NPs are made by decreasing ions of metals precursors in a chemical decreasing agent fluid. Metal NPs have used in different investigate fields, biomolecules imaging, and applications in the bio-analytical and environmental area. For instance, gold NP is applied in sample coating before imaging in the scanning electron microscope due to improving high-quality image [88,94,121].

2.3.1. Iron-based nanoparticles

Iron NPs have been used for modifying drilling fluids. Contreras et al. [122] studied the performance of drilling fluids with at high and low concentrations of iron-based and calcium-based NPs in HPHT condition (121 °C and 500 psi) and

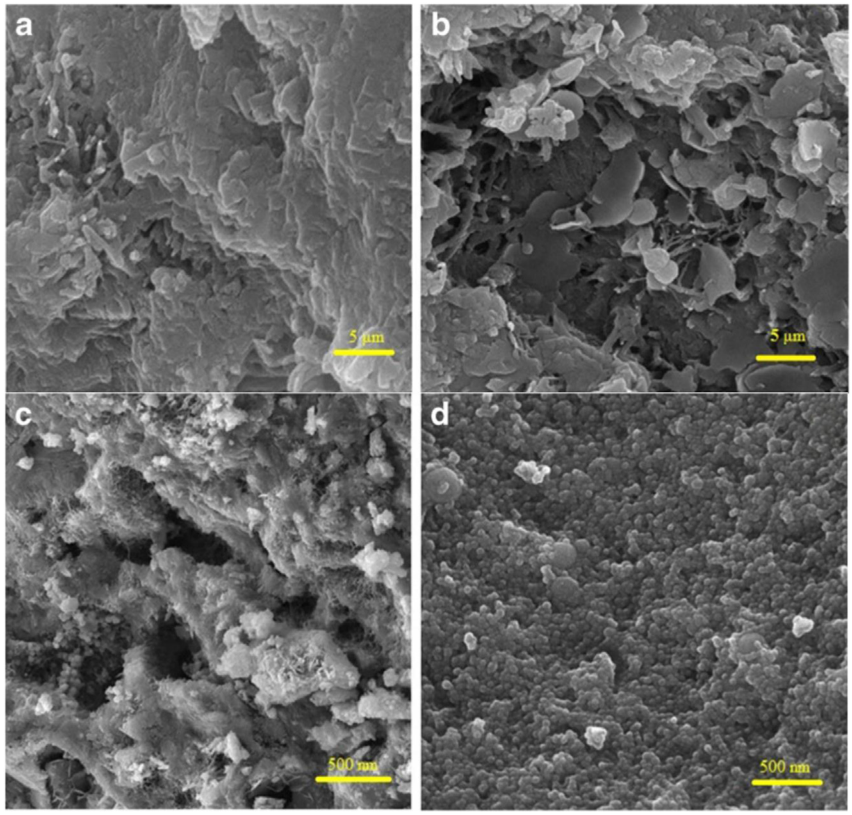

Fig. 2 – SEM images of mud cake a), surface; b), cross section; c), cross section with polymer/NPs, d), surface of pure polymer [101] with permission from Springer Nature.

permeable media (ceramic permeable). The results indicated that a reduction of 76% FL with adding metal NPs. Furthermore, they observed that if graphite applied with both NPs then FL could be achieved to 100%. In other investigation, Alvi et al., (2018) used iron nanoparticle in drilling fluids. The results indicated that the addition of boron nitride and iron NPs reduced the mechanical friction coefficients of drilling fluid. Iron NPs reduced the API static filtrate loss. The NPs have also shown an impact on viscosity parameters of drilling fluid [123].

2.3.2. *Calcium and Zirconium nanoparticles*

Contreras et al. (2016) considered the rheological characteristics of calcium NPs and their effect in permeable formation. They reported that optimum concentrations of calcium NPs enhanced the fracturing pressure by 63%, when compared to a base sample [124]. A recent research has been studied Zirconium oxide (ZrO_2) NPs effect on the filtration properties of WBMs. Paul and Adewale (2018) show that ZrO_2 NPs can reliably decrease thickness of mud cake and FL when added to water based mud. They found that the cake thickness and FL decreased with increment in NPs concentration [125].

2.3.3. *Silver nanoparticles*

A research on the use of a different NPs group was recently proposed by Husin et al., (2018). In this study, the use of silver nanoparticle (nanosilver) and graphene nanoplatelet together with WBM was investigated for producing NPs drilling fluid mixtures. Density, rheology, and filtration studies were evaluated based on conventional standardize tests. They concluded the silver NPs and the graphene nanoplatelet improved the plastic viscosity 64% and 89%, respectively. Moreover, both of the values of FL and yield point have decreased [126].

2.4. *Carbon-based nanoparticles*

Carbon-based NPs consist two major subcategories: fullerenes and carbon nanotubes. Carbon nanotubes are molecules of cylindrical that consist of rolled-up sheets of single-layer carbon atoms (graphene). Carbon-based NPs are mostly applied to reinforcing materials structural, as they are 100 times stronger than steel. Carbon nanotubes categorized to single-walled and multi-walled carbon nanotubes, SWCNTs and MWCNTs, respectively. Multi-walled carbon nanotubes are unique as they are non-conductive tube across and along the length have heat conductivity [94]. Fullerenes contain nanomaterial with globular hollow forms as carbon allotropic shapes [127,128]. Fullerenes have different forms and usages due to their high strength, structure, electrical conductivity, and electron affinity [94].

2.4.1. *Carbon nanoparticles*

A research on the use of a different NPs group was recently proposed by Ruqeishi et al., (2018). In this study, the use of carbon nanoparticles and ZnO nanowires together with WBM was investigated for producing NPs drilling fluid mixtures. Rheology and filtration studies were evaluated based on

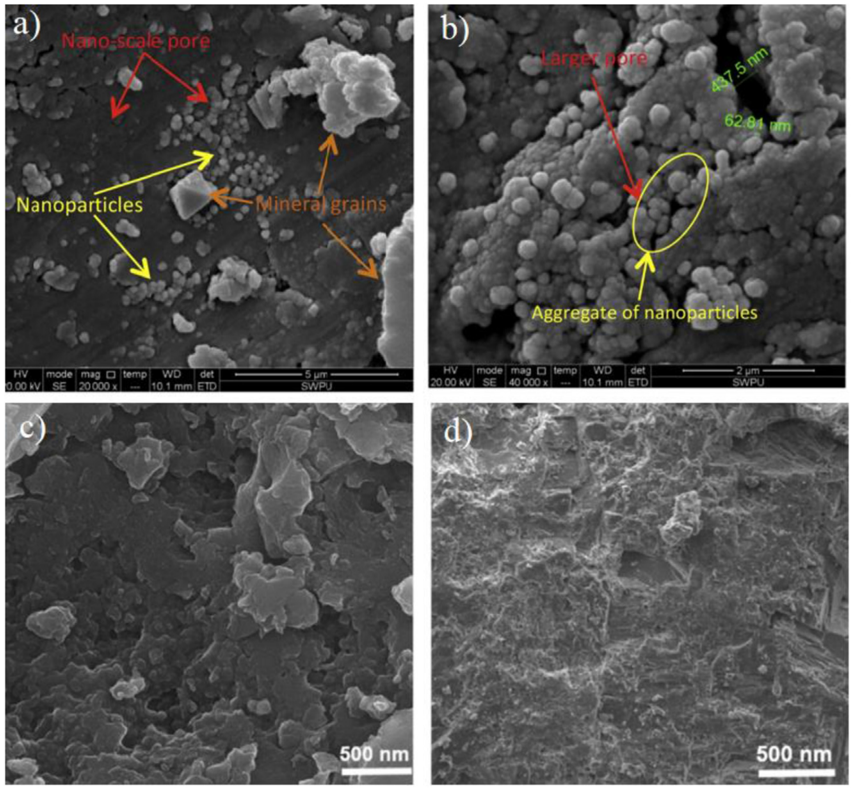

Fig. 3 – SEM images (a), NPs in shale and (b), plug a pore throat with NPs [58] with permission from Elsevier; FE-SEM images of filter cake of salt water drilling fluid (c), without and (d), with nanocomposite [78] with permission from Elsevier.

conventional standardize tests. They reported that the carbon nanoparticles could be delay effect of fluid sagging and maintaining the drilling fluid homogeneity for a longer period. Furthermore, the results showed that densities of drilling fluid improved 4–10% with 1–3 wt. % carbon nanoparticles and ZnO nanowires additives [129]. Passade et al. investigated effect and application of CNTs as drilling fluid in high temperature conditions [130]. The results showed the stability of thermal drilling fluid with CNTs at 325 °C or even higher. Paiaman and Al-Anazi [131] used of carbon black NPs as additive in drilling fluid and concluded improved thermal stability of fluids. Abduo et al. (2016) investigated multiwall carbon nanotubes to enhance the properties of water base drilling fluid under HPHT conditions; the results indicated that multiwall carbon nanotubes was improved temperature stability (up to 260 °C) as compared to conventionally fluid [132].

2.4.2. *Graphene nanoparticles*

Graphene is a graphite single layer which has unique properties and recently many researches have been carried out on it [105,133–135]. Graphene can be as a filter (pore-plug) in oil base drilling fluids. Although, due to the graphene dispersion problem in aqueous media, the graphene has poor

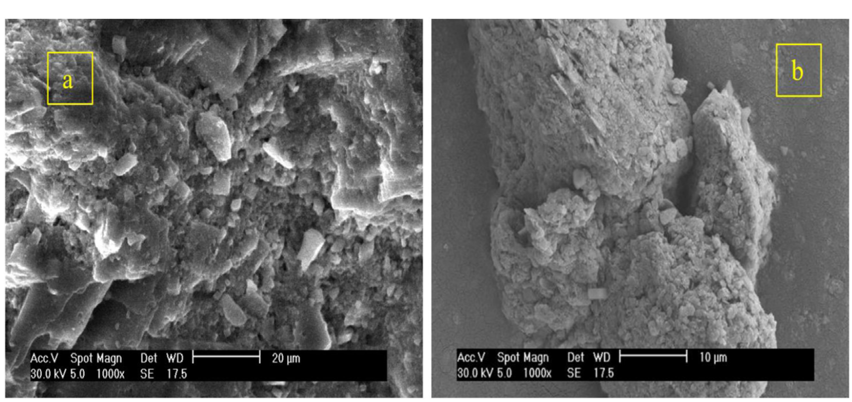

Fig. 4 – SEM pictures of filter cakes samples exposed to nano-drilling fluid. (bridging and plugging are two ways of sealing with NPs), a), base mud, b), mud containing TiO_2 NPs [115] with permission from Elsevier.

Table 2 – Reported type of nanoparticles used in drilling fluids and their behavior.

Author (s)	Type of nanoparticles	Fluid loss volume (mL)	Initial Gel strength (Pa)	10 min Gel strength (Pa)
Husin et al. [126]	Silver	2	–	–
Dejtaradon et al. [138]	CuO	12	16	35
Jain et al. [139]	MWCNT	9	4.5	7
Ismail [140]	Nanosilica	7	–	6
Kumar [141]	MWCNT	5	–	7
Abdo et al. [142]	Sepiolite	8	–	
Abdo et al. [143]	Montmorillonite	7	–	21.5
Dejtaradon et al. [138]	ZnO	14	15	37
Mao [36]	Silica	4.8	–	–
Aftab et al. [99]	ZnO	4.7	6	9
Kosynkin et al. [29]	Graphene Oxide	6.1	–	–
Jain et al. [144]	Silica	7.2	3.5	6.5
Ghasemi et al. [75]	Al_2O_3	–	15	39
Anawe et al. [65]	Yttrium Oxide	–	15	16
Smith et al. [25]	Al_2O_3	6	11	40
Zhang et al. [145]	$CaCO_3$	5.7	–	–
Cheraghian et al. [146]	Silica	10	13	32
Perween et al. [147]	$BiFeO_3$	7.8	13	20
Gbadamosi et al. [148]	Silica	5.1	7	8

performance in water base drilling fluids. While, graphene oxide has suitable stability in an aqueous medium [136,137].

The research carried out by Kosynkin in 2012 indicated graphene oxide NPs were improved mechanical properties of WBMs. In addition, they have evaluated effect of graphene oxide NPs on saline resistance in WBMs. They developed a reference drilling fluid sample containing 4 g/L by carbon content. The results indicated that both of powder and large-flake graphene oxide have potential for high-temperature application in oil and gas wells [29]. Some used types of nanoparticles and their behavior in drilling fluids summarized in Table 2.

3. Mechanical properties

3.1. *Rheology and fluid loss stability*

In a study by Medhi et al. (2019), the characteristics and properties of non-damaging drilling fluids with silica NPs were evaluated. The non-damaging drilling fluids in this investigation produced by polyamine. The experimental results indicated that silica NPs reduce 31% filtrate loss and thinning behavior of mud increase within NPs concentration [104]. Cheraghian (2017) investigated the effect of clay NPs on rheological and mechanical properties in water base drilling fluids. Experimental tests were conducted in static fluid-loss prepared with and without clay NPs consisting. The results showed nanoclay controls the fluid loss into the shale layers (Fig. 5a and b), thickness of mud cake and is resistant to high temperatures and also fluid loss. This research showed that the viscosity of solutions always with increased temperature decreased but this decrease rate change with add nanoparticles [118].

In another research, Aramendiz and Imqam (2019) added silica NPs in WBM and their results illustrated the novel drilling fluid can be decreased 35.61% shale cutting. Their results showed that the nanoparticles due to the repulsive forces between the NPs and the drilling fluid additives caused a slight reduction in PV [105]. More deeply, Boyou et al. [149] studied different concentrations silica NPs drilling solutions for increase drag and lift forces target. They concluded that NPs additives increase efficiency of cuttings transportation as well as, enhanced colloidal forces. In other mean, silica NPs present a network of particles in fluid and provide a better interaction between fluid and cutting surface at a turbulent rate in annulus of well. Their results showed that silica NPs in muds with high weight could reduce YP, PV, AV, and GS. Fig. 5c and d illustrates a modified schematic of this function.

The combination of polyethylene glycol and oxidized multi-walled carbon nanotube was investigated in a recent research work by Kazemi-Beydokhti and Hajiabadi (2018) to produce water-based drilling fluids polymer-modified NP drilling fluids. The results have been indicated that this formulation could properly decrease the permeability of mud cake, and also, reduce the filtration volume of NPs drilling fluid compared with that of base fluid. In addition, the rheological properties of mud such as viscosity, yield stress, and gel strength were considerably increased with their new hydrophilic formula [95]. In a similar research, Oseh et al. (2019) synthesized a high–temperature resistance nanocomposite. Evaluations showed that polypropylene and silica NPs could reduce filtration more than 22% and increased viscosity [96]. In a study by Hajiabadi et al. (2019), the rheological behaviors of drilling fluid with an optimized range of modified Multi-Walled Carbon Nano Tube (MWCNT) were addressed evaluated [150]. In order to investigate the formation of damage and porosity of core samples, they used Computed Tomography (CT) and imaging techniques. After testing, the results showed MWCNT create an isolated cake on the surface of sample and prevent deep penetration of the mud cake (Fig. 6). According to the SEM imaging analysis, mud cake without nano additives detected on both inlet and outlet faces of samples that is

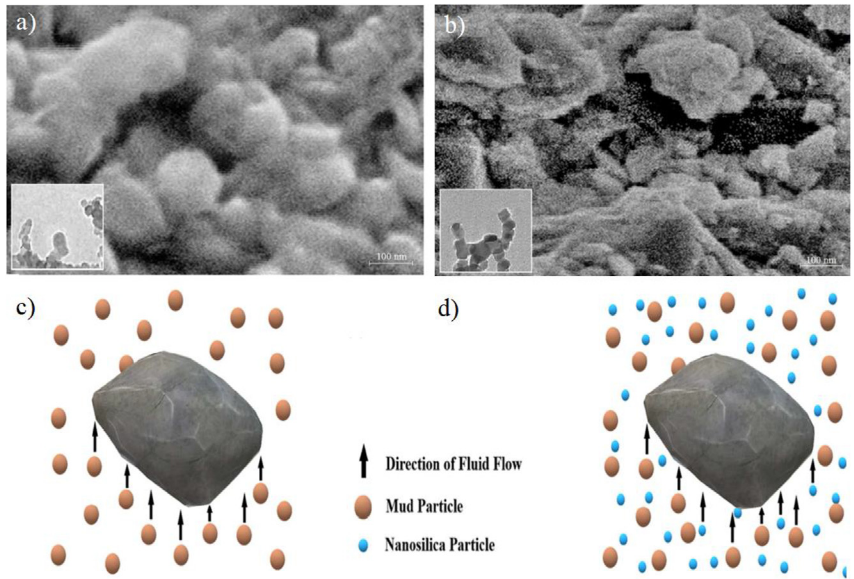

Fig. 5 – SEM images of the (a), clay- SiO_2 NPs, (b), SiO_2 NPs in permeable formations [45] with permission from Elsevier; Distribution of particles in flowing mud: (c), Basic mud and (d), Mud with nanosilica [149] with permission from Elsevier.

showing a high rate of damage, whilst, the samples tested by nano additives are much less damaged in their outlet faces (Fig. 7).

3.2. *Thermal stability*

There are some researches about high temperature/high pressure and high temperature/low pore pressure drilling fluids in recent years but they are still a huge challenge to drilling industries [151]. In recent years, numerous investigations have been reported for application of NPs as thermal stabilizer in the formulation of drilling fluids [152,153]. The possibility of incorporating magnesium, aluminum and silicate NPs in WB drilling fluid was investigated by Wang et al., (2018). The mixture prepared with the WB improved the rheological, filtration properties, and thermal stability. Moreover, the application of the magnesium aluminum silicate NPs in WB drilling could substantially decrease the use of conventional one, which is beneficial for environment [154]. In other research Gurluk et al. [155,156] studied the prospers of ZnO and MgO NPs with special surfactant (amidoamine oxide) in Calcium chloride and Calcium bromide solutions as drilling fluid. They concluded that NPs additives increase stability of thermal in surfactant visco-elastic solutions. Moreover, they concluded that the drilling fluids containing ZnO NPs, dominant factor become in elastic modulus system at 135 °C.

3.3. *Wellbore stability*

Many researchers have studied the effects of nano-materials on improving wellbore stability in unstable formations. The combination of polyethylene glycol and nano-silica was investigated in a recent research work by Xu et al. (2018). The results have indicated that this formulation could be an appropriate shale stabilizer in WBD. In addition, the blend was used as effective agent to plug shale pores and cracks [100]. Graphene derivatives can be as a filter (pore-plug) in oil base drilling fluids due to suitable stability in the aqueous medium [136,137]. However, the performance of graphene derivatives in water base drilling fluids is an issue because of poor dispersion in aqueous media.

More deeply, Liu et al. [157] studied the effect of silica NPs concentrations on properties of Pickering emulsion as a drilling fluid solution. They concluded that NPs additives increase stability of shale surfaces while prevent shale fractures. In a recent work, Pourkhalil and Nakhaee prepared novel nano-drilling fluid using different nano-ZnO concentrations (0.25%, 0.50% and 0.75%). Their results indicated positive charge, Hydrophilic and size behavior of NPs increase the shale stability. In other research Pourkhalil et al. [158] studied the prospers of modified ZnO NPs as drilling fluid. They concluded that NPs additives lead to blocking pore spaces in shale samples. Since zinc oxide nano-fluid is positively charged and hydrophilic can be adsorbed by shale particles (clay with negatively charged) and blocked the pore throats. The effect of additive Nano ZnO on a shale core is displayed by the SEM images in Fig. 8. As observed in Fig. 8, ZnO NPs widely disperse in cores and can bridge the pore throats.

4. Environmental and economic benefits from using nanoparticles in drilling fluid

The using of NP in drilling fluid has economic and environmental benefits. In addition to the improved performance of drilling fluid, one of the most important properties of nanoparticles is their low price [30]. In fact, the unique feature -huge surface area to the mass ratio, the reason for an increase in the reactivity of nanoparticles [159,160], and thus

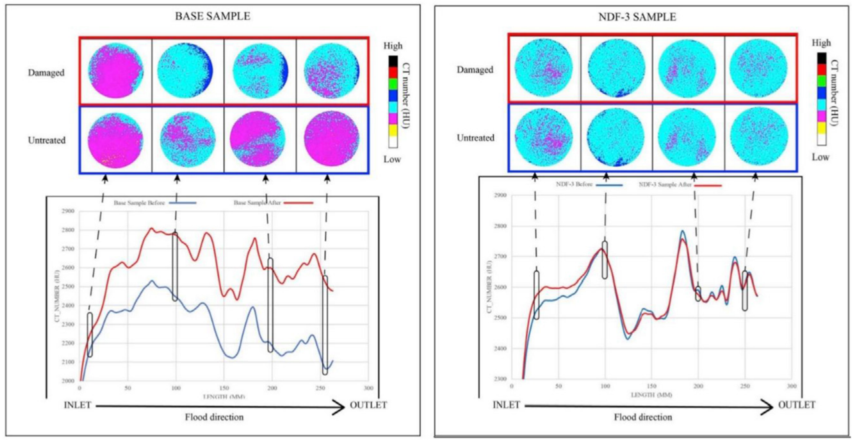

Fig. 6 – Recorded CT numbers variations as well as colored CT images from the original and damaged core samples [150] with permission from Elsevier.

leads to decrease NPs usage in drilling fluid and environmental problems of conventional drilling fluids.

NPs usage economically can be seen as having three aspects: NPs decrease cost of expensive materials drilling fluids [161,162]. As well as, ability drilling in challenging formations with NPs as drilling fluids lead to enhanced oil recovery [143]. Further, the nanoparticles save massive cost by reducing non-productive time [163].

5. Challenges

Even though the use of nanomaterials can bring significant technical benefits, however, the drawbacks concerning challenges of nanomaterials in drilling fluids cannot be ignored. Nanomaterials cost is a significant problem, which it should be, consider before start project. Generally, synthesis, services, and production process nanomaterials can be too costly

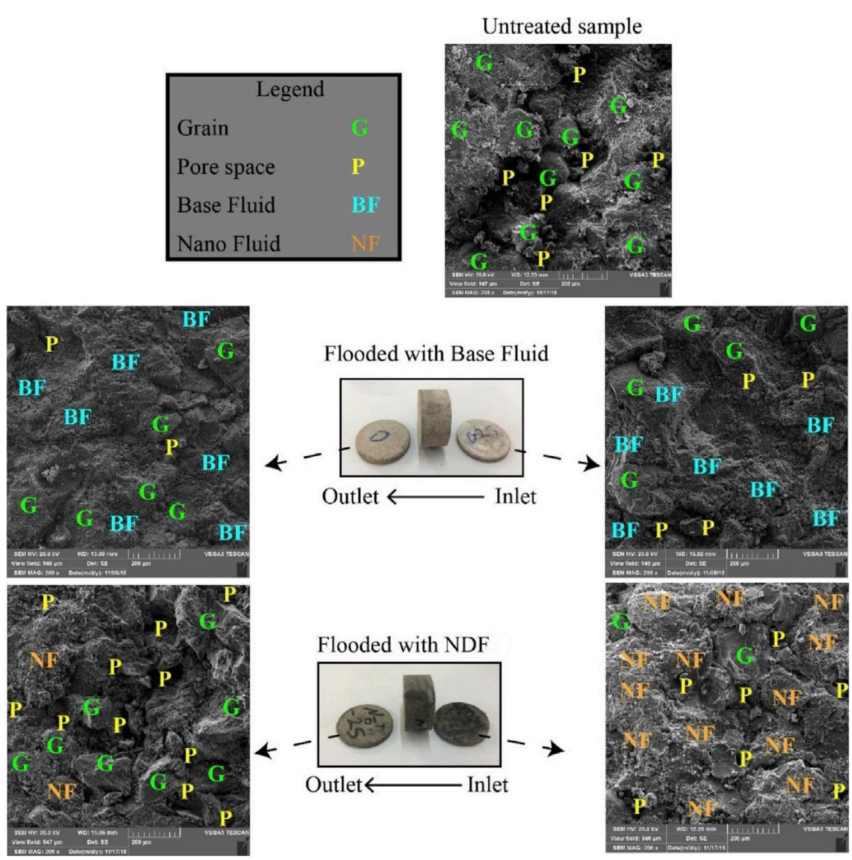

Fig. 7 – Showing SEM images from an untreated core slab, as well as, the internal part of the slabs trimmed from the inlet and outlet faces of the core samples flooded by the base flood and Nano drilling fluid [150] with permission from Elsevier.

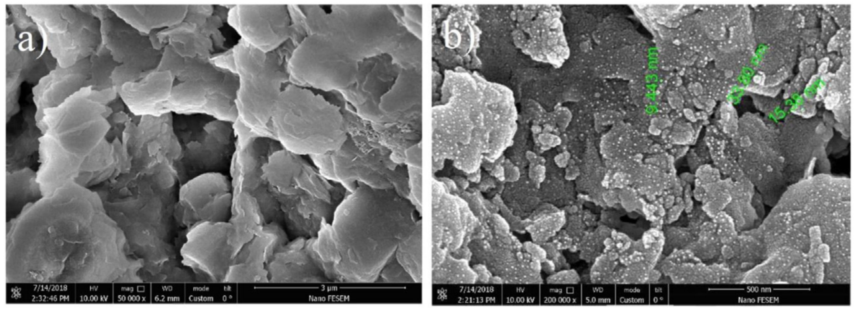

Fig. 8 – SEM images of shale cores, (a), before testing, (b), after testing with ZnO NPs [158] with permission from Elsevier.

and in the drilling operation should use a large volume of them in this process. Different conditions and unique properties of each oil field and well, and compatibility of nano fluids and nanoparticles with them are other important challenges in this issue. High temperature, chemical alterations and salinity in some formations can be the destructive agent to nanomaterial structure. Another issue related to the unknown of safety hazards and the health of nanomaterials [164,165]. Therefore, the use of standard industrial hygiene may significantly improve the safety hazards protection in drilling operations with nanomaterials. Since nanotechnology is a relatively new technology to produce new drilling fluids, there are only limited experimental and field test and analyses, knowledge, and experience on its long-term performance.

6. Conclusions

The present review reports the state of the art in the use of nano particles in drilling fluids. It presents the many of the NPs types, their properties and how they are tested, used in the mixing process, the types of applications in which NPs have been used in drilling fluids. Some conclusion can be drawn:

- The NPs has improved the heat tolerance, filtration characteristics, and rheological properties susceptibility of drilling fluids.
- The comprehensive mechanical properties of drilling fluids, compressive strength, rheological properties, thermal properties, and filter loss, were all improved by including NPs, and their improvements increased with an increment in the contents of NPs.
- Drilling fluids based on NPs could be possible solution of drilling under difficult conditions such as water sensitive shale and HPHT. Drilling fluids based on NPs could obviate the problems of wellbore instability, high filtrate volume, pipe sticking, and, shale swelling.
- Metal oxide and carbon NPs are suitable conductors to thermal properties and HPHT conditions. Further, recent applications of metal oxide nanocomposites and Polymeric NPs in drilling fluids are illustrated appropriate results of shale inhibition and rheological properties.
- The analysis results confirm the potential of NPs an environmentally alternative to materials for base applications in drilling fluids.

As more researchers pay attention to the NPs applied in drilling fluids, nano science and nanotechnology will help make greater progress in drilling fluid modifications. The review provides the most current information to the reader about advanced nano drilling fluids and a guide to the relevant articles for those who are new in this field.

Declaration of Competing Interest

I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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